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# Transverse energy flow in meson-proton and meson-nucleus interactions at 250 GeV/$c$

The EHS/NA22 Collaboration

M.R. Atayan[6], E.A. De Wolf[1,a], A.M.F. Endler[4], Z.Sh. Garutchava[5], N.G. Grigoryan[6], H. Gulkanyan[6], R. Hakobyan[6], J.K. Karamyan[6], W. Kittel[3], S. Mehrabyan[6], Z.V. Metreveli[5,b], F.K. Rizatdinova[2,c], E.K. Shabalina[2,d], L.N. Smirnova[2], L.A. Tikhonova[2], A.G. Tomaradze[5,b], F. Verbeure[1], S.A. Zotkin[2]

[1] Department of Physics, Universitaire Instelling Antwerpen, 2610 Wilrijk, Belgium
[2] Nuclear Physics Institute, Moscow State University, 119899 Moscow, Russia
[3] High Energy Physics Institute (HEFIN), University of Nijmegen/NIKHEF, 6525 ED Nijmegen, The Netherlands
[4] Centro Brasileiro de Pesquisas Fisicas, 22290 Rio de Janeiro, Brazil
[5] Institute for High Energy Physics of Tbilisi State University, 380086 Tbilisi, Georgia
[6] Institute of Physics, 375036 Yerevan, Armenia

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**Abstract.** The transverse energy carried by charged hadrons and by $\pi^-$ mesons is studied in interactions of $\pi^+$ and $K^+$ mesons with protons and nuclei at 250 GeV/$c$. The data obtained on transverse energy flow at mid-rapidity can be described by the FRITIOF7.0 model with tuned parameters.

## 1 Introduction

In nucleus-nucleus collisions, the transverse energy $E_T$ produced at mid-rapidity serves as a measure of the collision centrality. In order to establish a reliable relation between $E_T$ and the mean impact parameter $\langle b(E_T)\rangle$, information on $E_T$ flow in the 'elementary' hadron-nucleon (as well as hadron-nucleus) collisions is needed. The experimental data on $E_T$ production in hadron-nucleon and hadron-nucleus collisions are also necessary to tune event generators used for simulation of the multiparticle production processes. The data on meson-nucleon (meson-nucleus) collisions could, furthermore, be helpful in disentangling the underlying mechanisms in photoproduction reactions.

So far, a small number of calorimetric measurements of the transverse energy production have been performed in pA [1–3], pp and $\bar{p}p$ [4,5], as well as in ep [6,7] collisions. The only data for meson-proton collisions are reported in [5].

In this study, we partially fill a gap in the available data on the transverse energy flow in hadron-nucleon and hadron-nucleus collisions. To that end, we analyze the data on interactions of $\pi^+$ and $K^+$ mesons with protons and nuclei at 250 GeV/$c$, collected by the NA22 experiment at the CERN SPS. In Sect. 2 the experimental procedure is described. The data are presented in Sect. 3, compared with predictions of the FRITIOF [8,9] model in Sect. 4, where the model parameters are preliminarily tuned on inclusive spectra of particles produced in non-diffractive $\pi^+$p interactions. In Sect. 5, the model predictions are compared with data on proton-nucleus, heavy-ion and photon-proton interactions. The results are summarized in Sect. 6.

## 2 Experimental procedure

The experiment was performed at CERN in the European Hybrid Spectrometer equipped with the Rapid Cycling Bubble Chamber (RCBC) and exposed to a 250 GeV/$c$ tagged positive meson-enriched beam. The RCBC, filled with liquid hydrogen, was equipped with two nuclear targets consisting of an aluminium and a gold foil of thickness 2.5 mm and 0.64 mm, respectively, corresponding to 0.5% of an interaction length, and placed side by side orthogonally to the beam, 15.5 cm behind the entrance window of the chamber. The experimental setup and the trigger conditions are detailed in [10–13].

Charged-particle momenta are measured over the full solid angle with an average resolution varying from 1-2%

[a] Also at CERN, European Organisation for Particle Physics, 1211 Geneva 23, Switzerland
[b] Now at Northwestern University, Evanston, USA
[c] Now at Kansas State University, Manhattan, KS 66506, USA
[d] Now at University of Illinois at Chicago, Chicago, IL 60607, USA

for tracks reconstructed in RCBC and 1-2.5% for tracks reconstructed in the first lever arm, to 1.5% for tracks reconstructed in the full spectrometer. Ionization information is used to identify protons up to 1.2 GeV/$c$ and electrons (positrons) up to 200 MeV/$c$. All unidentified tracks are given the pion mass, except for the fast ($p$ >150 GeV/$c$) positive particle in kaon induced reactions, which is given the kaon mass.

The general event selection criteria for interactions in hydrogen and foils are described in [12,13]. Two samples of events are studied. In the first, all charged tracks of an event are required to be properly measured and reconstructed. In the second sample, this requirement is limited to negatively charged tracks. We exclude candidates for elastic scattering and single-diffractive dissociation with charged-particle multiplicity $n \leq 6$ (for meson-proton interactions), as well as candidates for meson-nucleus quasi-elastic or coherent interactions (see details in [6,7]).

The resulting number of selected events $N_{\rm tot}$ is 44956 for ($\pi^+$/K$^+$)p interactions for which all tracks are properly reconstructed; 69992 for ($\pi^+$/K$^+$)p, 3329 for ($\pi^+$/K$^+$)Al and 2294 for ($\pi^+$/K$^+$)Au interactions for which all negatively charged tracks are properly reconstructed. Each event is given a multiplicity-dependent weight which corrects for the fraction of events excluded due to improperly reconstructed tracks.

For each event, the transverse energy $E_{\rm T}^{\rm ch}$ carried by charged hadrons (identified pions and unidentified charged particles) and $E_{\rm T}^{\pi^-}$ carried by negative pions, emitted in a given (pseudo)rapidity window, is calculated as the sum of individual transverse energies $\varepsilon_i \sin\vartheta_i$, where $\varepsilon_i$ is the total energy of $i$-th hadron and $\vartheta_i$ is its emission angle in the laboratory frame.

Due to the misidentification of a fraction of charged particles, the values of $E_{\rm T}^{\rm ch}$ and $E_{\rm T}^{\pi^-}$ are biased. These biases, estimated by simulations using the FRITIOF7.0 model, result in an overestimation (underestimation) of $\langle E_{\rm T}^{\rm ch}\rangle$ ($\langle E_{\rm T}^{\pi^-}\rangle$) on the average by 2% (0.8%) in the pseudorapidity range 1.5< $\eta$ <4.5 and by 5% (6%) in the target fragmentation region ($\eta$ <1.5). In the beam fragmentation region ($\eta$ >4.5) the corrections are negligible. The experimental data presented below are not corrected for these biases, since correction would be model dependent, but corresponding biases have been introduced in the model calculations.

Since no statistically significant differences are seen between the results for $\pi^+$ and K$^+$ induced reactions, the two data samples are combined for the purpose of this analysis.

## 3 Experimental results

### 3.1 Meson-proton interactions

The dependence of the mean transverse energy $\langle E_{\rm T}^{\rm ch}\rangle$ and $\langle E_{\rm T}^{\pi^-}\rangle$ carried by charged hadrons (mainly $\pi^+$ mesons) and by negatively charged hadrons (the overwhelming fraction (93±3)% of which are $\pi^-$ mesons [14]) on the pseudorapidity $\eta$ and the c.m.s. rapidity $y$ for ($\pi^+$/K$^+$)p collisions is plotted in Fig. 1. The maximum transverse energy per unit of (pseudo)rapidity is $\langle E_{\rm T}^{\rm ch}\rangle/\Delta\eta \approx \langle E_{\rm T}^{\rm ch}\rangle/\Delta y \approx$0.77 GeV for charged particles and $\langle E_{\rm T}^{\pi^-}\rangle/\Delta\eta \approx \langle E_{\rm T}^{\pi^-}\rangle/\Delta y \approx$0.34 GeV for $\pi^-$ mesons. In the central rapidity region $-2 < y < 2$ (or, equivalently, 1< $\eta$ <5), the data can be approximated by a Gaussian form of width $\sigma^{\rm ch}$=2.11±0.02 and centroid $y_0^{\rm ch}$=0.279±0.010 for charged particles and $\sigma^{\pi^-}$=1.62±0.01 and $y_0^{\pi^-}$=0.267±0.007 for $\pi^-$ mesons (for model comparisons see Sect. 4 below).

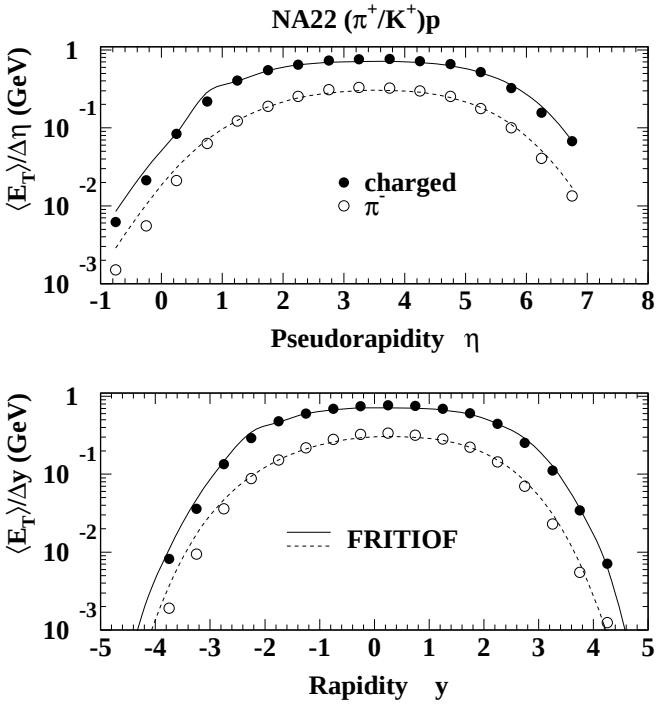


**Fig. 1.** The pseudorapidity and c.m.s. rapidity dependence of $\langle E_{\rm T}^{\rm ch}\rangle$ and $\langle E_{\rm T}^{\pi^-}\rangle$ in ($\pi^+$/K$^+$)p interactions. The full and dashed curves are FRITIOF7.0 predictions for $\langle E_{\rm T}^{\rm ch}\rangle$ and $\langle E_{\rm T}^{\pi^-}\rangle$, respectively

The data for fixed charged-particle multiplicity $n$ (and $\pi^-$ meson multiplicity $n_{\pi^-}$=($n$−2)/2) presented in Fig. 2, show that the Gaussian approximation is not valid for the lowest multiplicities ($n \leq$6). The results of the Gaussian fits for $n \geq$8 ($n_{\pi^-} \geq$3) are presented in Tables 1 and 2. With increasing multiplicity, the shape of the distributions narrows significantly, while the maximum tends to converge towards the value of $\eta_c$=3.14 corresponding to pions with $p_{\rm T} \gg m_\pi$ emitted at the c.m.s. angle $\vartheta^*$=90°. The distributions for $\pi^-$ mesons are narrower, especially at lower multiplicities, than for charged particles. As can be seen from Tables 1 and 2, each additional pair of charged particles (mainly $\pi^+\pi^-$) increases $\left(\mathrm{d}\langle E_{\rm T}^{\rm ch}\rangle/\mathrm{d}\eta\right)_{\rm max}$ on average by 0.27±0.04 GeV, while each $\pi^-$ increases $\left(\mathrm{d}\langle E_{\rm T}^{\pi^-}\rangle/\mathrm{d}\eta\right)_{\rm max}$ on average by 0.12±0.02 GeV, except for the largest multiplicity $n_{\pi^-}$=10 for which the increase is 0.29±0.06 GeV. These features, inherent to hadron-nucleon collisions, are important when considering the

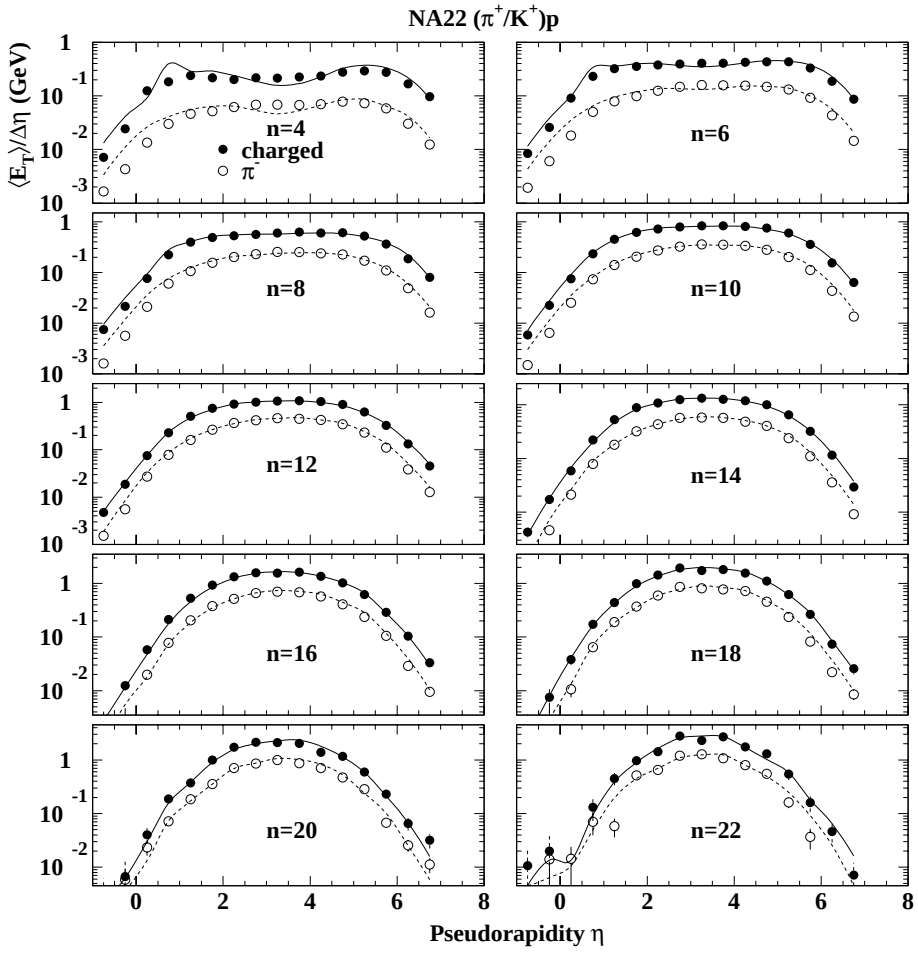


**Fig. 2.** The pseudorapidity dependence of $\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle$ and $\langle E_{\mathrm{T}}^{\pi^-}\rangle$ for fixed multiplicities in $(\pi^+/\mathrm{K}^+)$p interactions. The full and dashed curves are FRITIOF7.0 predictions for $\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle$ and $\langle E_{\mathrm{T}}^{\pi^-}\rangle$, respectively

**Table 1.** Results of the Gaussian fit (for $1< \eta <5$) of the pseudorapidity dependence of $\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle$ for different charged-particle multiplicities $n$ for $(\pi^+/\mathrm{K}^+)$p non-diffractive interactions

| $n$ | $(\mathrm{d}\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle/\mathrm{d}\eta)_{\max}$ GeV | $\sigma^{\mathrm{ch}}$ | $\eta_0^{\mathrm{ch}}$ |
|---|---|---|---|
| 8 | $0.621 \pm 0.004$ | $2.96 \pm 0.11$ | $3.97 \pm 0.08$ |
| 10 | $0.855 \pm 0.006$ | $2.14 \pm 0.04$ | $3.57 \pm 0.03$ |
| 12 | $1.102 \pm 0.009$ | $1.90 \pm 0.04$ | $3.52 \pm 0.03$ |
| 14 | $1.357 \pm 0.014$ | $1.66 \pm 0.03$ | $3.42 \pm 0.02$ |
| 16 | $1.675 \pm 0.024$ | $1.41 \pm 0.03$ | $3.34 \pm 0.02$ |
| 18 | $1.950 \pm 0.041$ | $1.28 \pm 0.03$ | $3.34 \pm 0.03$ |
| 20 | $2.270 \pm 0.083$ | $1.11 \pm 0.04$ | $3.28 \pm 0.04$ |
| 22 | $2.526 \pm 0.160$ | $1.15 \pm 0.08$ | $3.37 \pm 0.07$ |

**Table 2.** Results of the Gaussian fit (for $1< \eta <5$) of the pseudorapidity dependence of $\langle E_{\mathrm{T}}^{\pi^-}\rangle$ for different multiplicities $n_{\pi^-}$ for $(\pi^+/\mathrm{K}^+)$p non-diffractive interactions

| $n_{\pi^-}$ | $(\mathrm{d}\langle E_{\mathrm{T}}^{\pi^-}\rangle/\mathrm{d}\eta)_{\max}$ | $\sigma^{\pi^-}$ | $\eta_0^{\pi^-}$ |
|---|---|---|---|
| 3 | 0.259±0.002 | 1.87±0.04 | 3.67±0.03 |
| 4 | 0.362±0.003 | 1.68±0.03 | 3.54±0.02 |
| 5 | 0.475±0.004 | 1.56±0.02 | 3.48±0.02 |
| 6 | 0.600±0.007 | 1.43±0.02 | 3.41±0.02 |
| 7 | 0.717±0.011 | 1.34±0.03 | 3.33±0.02 |
| 8 | 0.872±0.020 | 1.23±0.03 | 3.35±0.03 |
| 9 | 0.990±0.037 | 1.14±0.04 | 3.33±0.04 |
| 10 | 1.280±0.081 | 0.96±0.04 | 3.39±0.06 |

nucleus-nucleus interactions as a superposition of "elementary" nucleon-nucleon collisions.

The distributions $(1/N_{\mathrm{tot}})(\mathrm{d}N/\mathrm{d}E_{\mathrm{T}})$ of the transverse energy per event carried by charged and negative particles emitted in the $y$ window of $-1.5< y <1.5$ are plotted in Fig. 3. The first (low $E_{\mathrm{T}}$) point corresponds (mainly) to events for which no charged or no negative particles are produced in that window. The extracted average values of $\langle E_{\mathrm{T}}\rangle$ are $\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle$=2.132±0.007 GeV and $\langle E_{\mathrm{T}}^{\pi^-}\rangle$=0.892± 0.003 GeV. The transverse energy carried by positively charged hadrons, $\langle E_{\mathrm{T}}{}^{\mathrm{pos}}\rangle = \langle E_{\mathrm{T}}{}^{\mathrm{ch}}\rangle - \langle E_{\mathrm{T}}{}^{\pi^-}\rangle$ = 1.24± 0.01 GeV, is 1.4 times $\langle E_{\mathrm{T}}{}^{\pi^-}\rangle$.

In view of the current and anticipated investigations of lepton-pair production in nuclear collisions, it is important to have experimental data on the transverse energy $\langle E_{\mathrm{T}}^{\mathrm{ch}}\rangle_a$ carried by charged hadrons accompanying a pair of charged mesons, the main source of background for

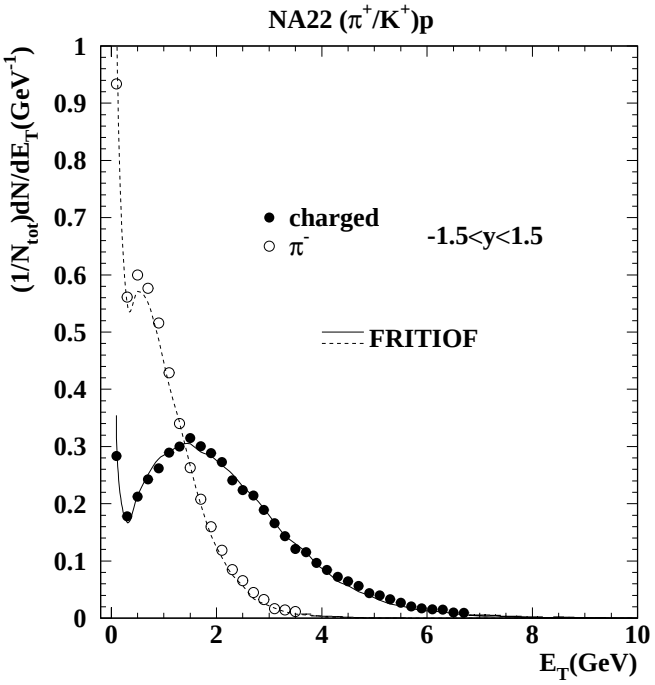


**Fig. 3.** The $E_{\rm T}^{\rm ch}$ and $E_{\rm T}^{\pi^-}$ distributions at mid-rapidity (-1.5 < $y$ < 1.5) in ($\pi^+$/K$^+$)p interactions. The full and dashed curves are FRITIOF7.0 predictions for $E_{\rm T}^{\rm ch}$ and $E_{\rm T}^{\pi^-}$, respectively

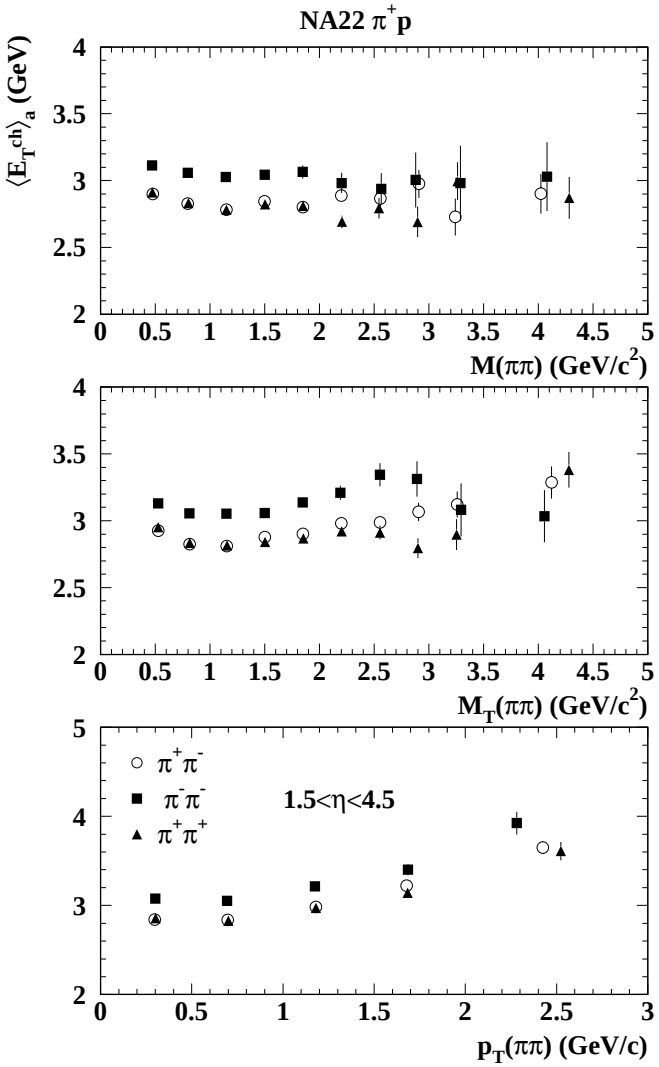


**Fig. 4.** The dependence of the associated transverse energy $\langle E_{\rm T}^{\rm ch}\rangle_{\rm a}$ on the mass, transverse mass and transverse momentum of an accompanying dipion produced in the window of 1.5 < $\eta$ < 4.5 in $\pi^+$p interactions

dimuons. Figure 4 demonstrates the dependence of $\langle E_{\rm T}^{\rm ch}\rangle_a$ (for 1.5< $\eta$ <4.5) on the effective mass $M(\pi\pi)$, the transverse mass $M_{\rm T}(\pi\pi)$ and the transverse momentum $p_{\rm T}(\pi\pi)$ of a pair of charged hadrons (mainly $\pi^+\pi^-$, $\pi^+\pi^+$, $\pi^-\pi^-$) emitted into that $\eta$ window. Note, that the value $\langle E_{\rm T}^{\rm ch}\rangle_a$ associated with a pair of negatively charged pions is higher than for ($\pi^+\pi^+$) and ($\pi^+\pi^-$) pairs, because events of $n \leq 4$ can contribute to the latter, while $n \geq 6$ holds for the former. Whereas no clear dependence is observed on $M(\pi\pi)$, $\langle E_{\rm T}^{\rm ch}\rangle_a$ clearly increases with increasing $p_{\rm T}(\pi\pi)$. At least for the opposite-sign pair, $\langle E_{\rm T}^{\rm ch}\rangle_a$ also tends to rise with increasing $M_{\rm T}(\pi\pi)$. The observed dependence can induce a small apparent difference in the extracted mean impact parameter for low and high $p_{\rm T}(M_{\rm T})$ dimuons produced in very peripheral nucleus-nucleus collisions, in which only a few nucleons participate.

### 3.2 Meson-nucleus interactions

The (pseudo)rapidity dependence of $\langle {E_{\rm T}}^{\pi^-}\rangle$ produced in collisions with Al and Au nuclei is shown in Fig. 5, where the hydrogen data are repeated for comparison. The nucleus to proton ratio $r_{\rm A} = \langle {E_{\rm T}}^{\pi^-}\rangle_{\rm A}/\langle {E_{\rm T}}^{\pi^-}\rangle_{\rm p}$ (bottom Fig. 5) continuously increases with decreasing $y$ and reaches $r_{\rm Al}$=9.5±1.1 and $r_{\rm Au}$=16.3±1.6 at -3.5< $y$ < −3, evidencing the essential role of secondary interactions of produced pions in the nucleus. In the beam fragmentation region ($y$ >2), the values of $\langle {E_{\rm T}}^{\pi^-}\rangle_{\rm Al}$ and $\langle {E_{\rm T}}^{\pi^-}\rangle_{\rm Au}$ are almost equal, but smaller than that for meson-proton interactions, especially at larger $y$ (3< $y$ < 3.5), where $r_{\rm Al}$=0.29±0.04 and $r_{\rm Au}$=0.34±0.05, indicating strong attenuation effects during the passage of the leading projectile (the leading string) through the nucleus. As the mean number of collisions of the leading meson in Al and Au is $\langle\nu_{\rm Al}\rangle$ ≈1.7 and $\langle\nu_{\rm Au}\rangle$ ≈2.8 [15], respectively, one can deduce that the attenuation effects influencing $\langle {E_{\rm T}}^{\pi^-}\rangle$ ($y$ >2) saturate already after a couple of intranuclear collisions of the leading excited string. Similar features have been observed [15] for the yields $\langle n_{\pi^-}\rangle$ of the high-rapidity $\pi^-$ mesons.

Mainly due to intranuclear interactions of the produced $\pi^-$ mesons, the centroid of the Gaussian approximation (for −2< $y$ <2) of the data plotted in Fig. 5 shifts, with increasing $A$, towards smaller values, $y_0^{\pi^-}$(Al)= −0.23±0.04 and $y_0^{\pi^-}$(Au)= −0.52±0.05, as compared to $y_0^{\pi^-}$(p)=+0.267±0.007 for meson-proton interactions. Some (minor) role in this shift can be played by the neu-

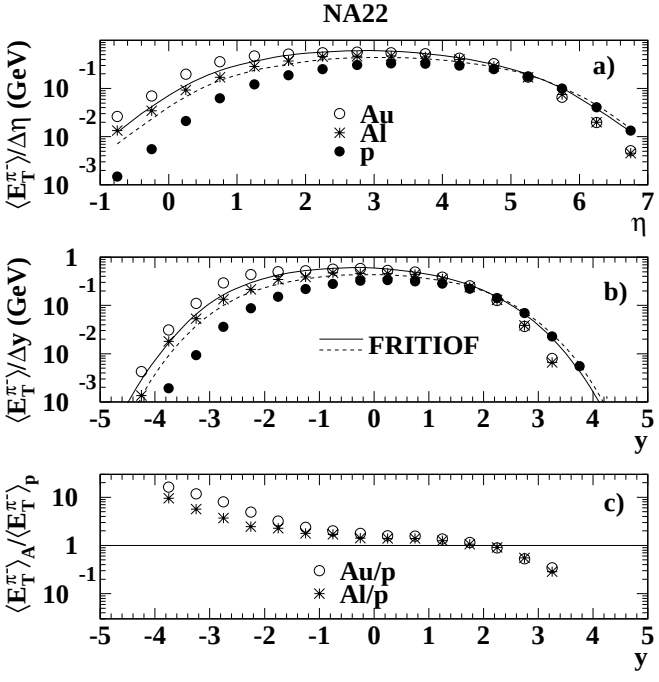


**Fig. 5.** The pseudorapidity (top) and c.m.s. rapidity (middle) dependence of $\langle E_{\rm T}^{\pi^-}\rangle$ in ($\pi^+$/K$^+$) interactions with p, Al, Au, and c.m.s. rapidity dependence (bottom) of the nucleus to proton ratio, $\langle E_{\rm T}^{\pi^-}\rangle_{\rm A}/\langle E_{\rm T}^{\pi^-}\rangle_{\rm p}$. The full and dashed curves are FRITIOF7.0 predictions for Au and Al nuclei, respectively

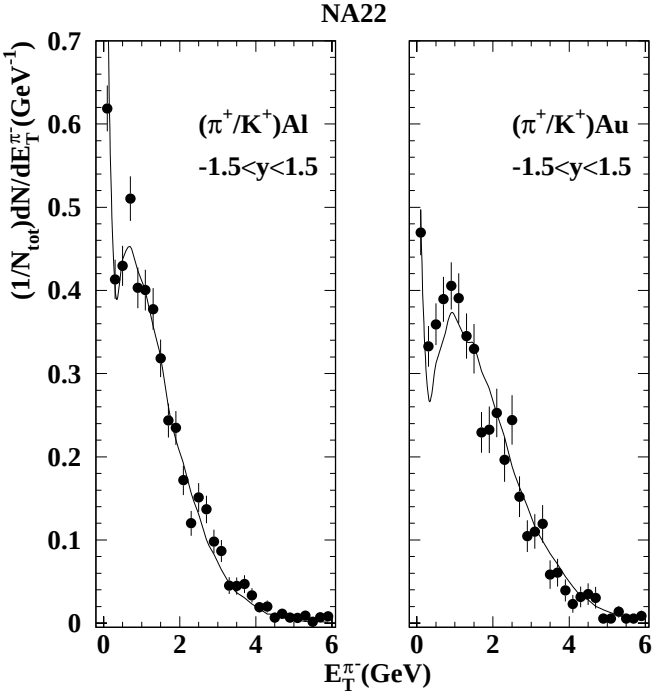


**Fig. 6.** The $E_{\rm T}^{\pi^-}$ distribution at mid-rapidity ($-1.5< y <1.5$) in ($\pi^+$/K$^+$)Al and ($\pi^+$/K$^+$)Au interactions. The curves are the FRITIOF7.0 predictions

tron content of the target: neutron fragmentation produces more $\pi^-$ mesons than proton fragmentation. The fitted widths of the Gaussian approximation, $\sigma_{\rm Al}^{\pi^-}$=1.72± 0.05 and $\sigma_{\rm Au}^{\pi^-}$=1.82±0.07, turn out to be somewhat larger than that for meson-proton interactions ($\sigma^{\pi^-}$=1.62± 0.01).

The distributions $(1/N_{\rm tot})({\rm d}N/{\rm d}E_{\rm T}^{\pi^-})$ in the transverse energy carried by $\pi^-$ mesons emitted in the window $-1.5< y <1.5$ in ($\pi^+$/K$^+$)Al and ($\pi^+$/K$^+$)Au interactions are plotted in Fig. 6. With increasing $A$, the distribution widens towards higher $E_{\rm T}^{\pi^-}$, and its mean value increases from $\langle E_{\rm T}^{\pi^-}\rangle_{\rm p}$=0.878±0.003 GeV to $\langle E_{\rm T}^{\pi^-}\rangle_{\rm Al}$=1.31± 0.02 GeV and $\langle E_{\rm T}^{\pi^-}\rangle_{\rm Au}$=1.53±0.03 GeV. Under the assumption of a power-law parametrization of $\langle E_{\rm T}^{\pi^-}\rangle_A \sim A^\alpha$, the value of $\alpha$ fitted to the combined hydrogen and nuclear data is $\alpha$ =0.11±0.01. A fit to the nuclear data alone yields $\alpha$ =0.08±0.01.

## 4 Comparison with model predictions

The experimental data are compared with predictions of the FRITIOF7.0 model [8,9]. An important ingredient of the model is the (semi)hard scattering of the partons (mainly gluons) of the colliding hadrons (the Rutherford Parton Scattering, RPS), which was found to be necessary to reproduce the high-multiplicity tail of the charged-particle distribution in high energy hadron collisions. The most essential model parameter which governs the RPS probability is the minimum transverse momentum $q_{\rm Tmin}$ acquired by the scattered gluon. Even though still low in the tail, reasonable agreement with the measured multiplicity distribution of non-diffractive $\pi^+$p interactions [11, 16] is reached for $q_{\rm Tmin}$=0.6 GeV/$c$, as demonstrated in Fig. 7a. The events with $n \leq$6 satisfying the criteria of the single-diffractive dissociation [16] are excluded both from experimental data and simulated events. Note that for the "default" value of $q_{\rm Tmin}$=1 GeV/$c$ [9], the model prediction is worse. In the following, we adopted the value $q_{\rm Tmin}$=0.6 GeV/$c$.

The model ingredients essentially influencing the predicted transverse momentum distribution of final hadrons are: the distribution of the soft transverse momentum transfer $Q_{\rm T}$ between the two colliding strings; the distribution of the primordial transverse momentum $Q_{\rm 2T}$ carried by the string ends (valence quarks or diquarks) of a string; the distribution of the transverse momentum ($p_x$ and $p_y$ in the string reference frame) acquired by direct (primary) hadrons as a result of string fragmentation. All these distributions are assumed to have a Gaussian form.

The width of the $p_x$ ($p_y$) distribution is taken from the OPAL setting: $\sigma_x = \sigma_y = 0.37$ GeV/$c$ [17].

The value of $\langle Q_{\rm 2T}^2\rangle$ adopted in deep inelastic lepton-proton collisions is $\langle Q_{\rm 2T}^2\rangle_{\rm DIS}$ =0.42 (GeV/$c$)$^2$ [18,19]. The (semi-hard) hadron-hadron interactions are governed by a larger scale hadron structure corresponding to smaller primordial transverse momentum of valence quarks (diquarks). Hence, smaller values of $\langle Q_{\rm 2T}^2\rangle$ (up to about

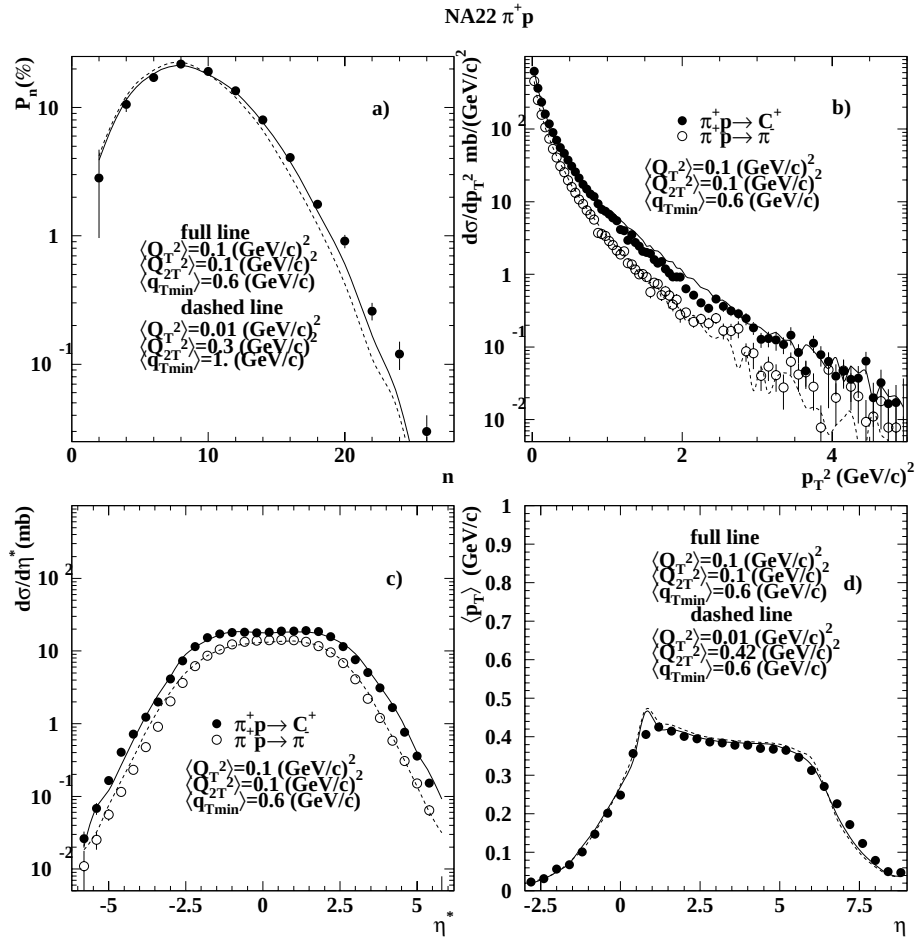


**Fig. 7. a** The charged-particle multiplicity distribution in $\pi^+$p interactions. The curves are the FRITIOF7.0 predictions for two different sets of parameters; **b** The $p_{\rm T}^2$ distribution for positively charged hadrons $C^+$ (mainly $\pi^+$ and p) and negatively charged hadrons (mainly $\pi^-$); FRITIOF7.0: full and dashed lines, respectively; **c** The c.m.s. pseudorapidity distributions for positively and negatively charged hadrons; **d** The $\eta$-dependence of the mean transverse momentum for charged hadrons. The curves are FRITIOF7.0 predictions at two different sets of parameters

0.1 (GeV/$c$)$^2$) should be used in the model (note, that $\langle Q_{\rm 2T}^2\rangle_{\rm default}$=0.3 (GeV/$c$)$^2$).

For $\langle Q_{\rm T}^2\rangle$ we use a larger value than the "default" one $\langle Q_{\rm T}^2\rangle_{\rm default}$=0.01 (GeV/$c$)$^2$. Even in single-diffractive scattering the squared transverse momentum acquired by the excited hadron state is $\langle Q_{\rm T}^2\rangle_{\rm diff}$=0.1−0.15 (GeV/$c$)$^2$, while in non-diffractive processes it is $\langle Q_{\rm T}^2\rangle_{\rm non-diff}$=0.1−0.4 (GeV/$c$)$^2$ [20,21].

We tried to tune the parameters $\langle Q_{\rm 2T}^2\rangle$ and $\langle Q_{\rm T}^2\rangle$ on the experimental inclusive spectra of positively and negatively charged hadrons produced in non-diffractive $\pi^+$p interactions at 250 GeV/$c$. A reasonable description of $p_{\rm T}^2$ and $\eta^*$−distributions (Figs. 7b and 7c) is achieved for two sets of parameters (leading to practically indiscernible predictions): $\langle Q_{\rm T}^2\rangle$=$\langle Q_{\rm 2T}^2\rangle$=0.1 (GeV/$c$)$^2$, and $\langle Q_{\rm T}^2\rangle$= 0.01 (GeV/$c$)$^2$, $\langle Q_{\rm 2T}^2\rangle$=0.42 (GeV/$c$)$^2$. A slightly better description of the $\eta$−dependence of the mean transverse momentum of charged hadrons (Fig. 7d) is provided by the first set of parameters, which are finally chosen for comparison with the transverse energy spectra.

With tuned parameters, the model describes satisfactorily the transverse energy data in ($\pi^+$/K$^+$)p collisions (Figs. 1−3), only slightly underestimating the data in the central (pseudo)rapidity region. This underestimation holds also for ($\pi^+$/K$^+$)Al data, while better agreement in the central (pseudo)rapidity region is achieved for ($\pi^+$/K$^+$)Au data (Fig. 5). Since secondary intranuclear interactions of the produced hadrons are not included in the model, is unable to reproduce the enhanced transverse energy flow in the target fragmentation region ($\eta$ <1 or $y$ < −2), especially for the case of the (heavier) Au target. The model also overestimates the data in the beam fragmentation region ($\eta$ >5 or $y$ >2), which can be caused by a underestimation of the multiple scattering effects during the passage of the leading string through the nucleus. Nevertheless, the model reproduces well the $E_{\rm T}^{\pi^-}$ distribution at mid-rapidity (-1.5< $y$ <1.5) for meson-nucleus interactions (Fig. 6).

In so far as the FRITIOF7.0 model provides a satisfactory description of hadronic interactions, its predictions for hadron-nucleus and heavy-ion collisions can, in a comparison with experimental data, serve as a reference for a quantitative estimation of secondary intranuclear collision effects.

## 5 Comparison with other data

The FRITIOF7.0 predictions obtained with the same parameters as used in Sect. 4, have been compared in Figs. 8 and 9a with the $\eta$-dependence of the transverse energy $E_{\rm T}$ at different centralities of proton-nucleus [3] and heavy-ion

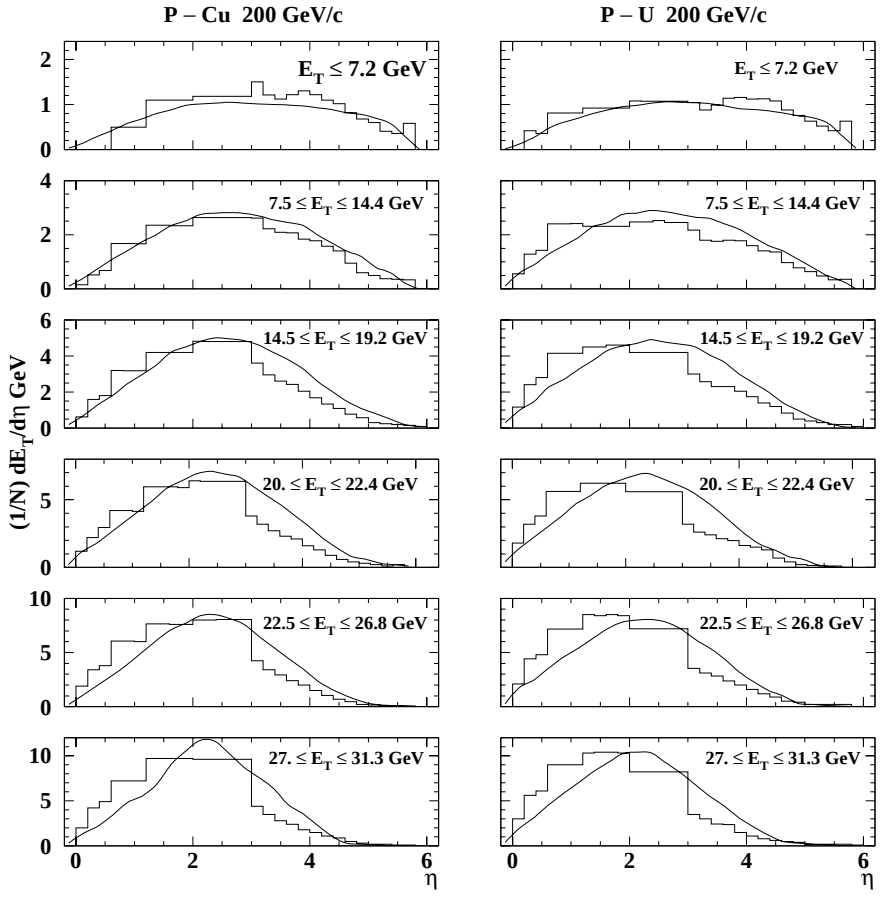


**Fig. 8.** The pseudorapidity dependence of $E_{\mathrm{T}}$ in pCu and pU interactions at 200 GeV/$c$ in different $E_{\mathrm{T}}$ slices. The curves are FRITIOF7.0 predictions

[22] collisions. The simulated events are selected according to appropriate experimental trigger conditions. A comparison with pCu and pU interactions at 200 GeV [3] is shown in Fig. 8. For non-central collisions ($E_{\mathrm{T}}$ ≤14.4 GeV), which comprise a large fraction of cross section (84% for pCu and 66% for pU interactions), the model qualitatively reproduces the data (taking into account 8% systematical errors in the data [3]). For central collisions ($E_{\mathrm{T}}$ ≥14.5 GeV), the model fails in describing the data in the target fragmentation region (especially for the heavier nucleus) and in the region $\eta > 3$. However, the predictions for the transverse energy emitted in a restricted mid-rapidity region, $1.9 < \eta < 2.9$, agree with the data within an accuracy of about 10% for Cu and about 15% for U.

The comparison with 200$A$ GeV S+Au data shows (Fig. 9a), that the model qualitatively reproduces the data for peripheral collisions ($7 < b < 11.5$ fm) in a wide $\eta$-range, as well as the data for intermediate centralities ($3.8 < b < 7$ fm) in the mid-rapidity range of $1.7 < \eta < 3$. As is the case of pA collisions, the model fails in describing the data for $\eta > 3$, especially for the most central collisions ($b < 3.8$ fm).

Finally, we compare the model predictions for $\pi^{\pm}$p collisions with the photoproduction data [6] on $\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta^*$ at HERA energies ($\sqrt{s}$=W≈180 GeV) and with the deep-inelastic scattering results for virtual-photon proton collisions (mean virtuality $Q^2 = 3.5$ GeV$^2$) [7] plotted in Fig. 9, where $\eta^*$ is defined in the hadronic c.m.s., negative values of $\eta^*$ now corresponding to the photon (pion) fragmentation region. Despite non-negligible systematic errors in the data (varying from 8–9% for $\eta^* > -3.5$ up to 20% for $\eta^* < -3.5$) for photoproduction, a clear shift toward larger $\eta^*$ is seen of the model predictions as compared to the HERA data.

## 6 Summary

New experimental results are presented on the mean transverse energy, $\langle E_{\mathrm{T}}^{\mathrm{ch}} \rangle$, carried by charged hadrons in ($\pi^+$/$\mathrm{K}^+$)p interactions and the transverse energy $\langle E_{\mathrm{T}}^{\pi^-} \rangle$ carried by negative hadrons in collisions of ($\pi^+$/$\mathrm{K}^+$) mesons with hydrogen, aluminium and gold nuclei at 250 GeV/$c$. The (pseudo-)rapidity dependence of $\langle E_{\mathrm{T}}^{\mathrm{ch}} \rangle$ and $\langle E_{\mathrm{T}}^{\pi^-} \rangle$ in the whole (pseudo)rapidity range, as well as the distributions of $E_{\mathrm{T}}^{\mathrm{ch}}$ and $E_{\mathrm{T}}^{\pi^-}$ for particles emitted at mid-rapidity are measured. The dependence of $\langle E_{\mathrm{T}}^{\mathrm{ch}} \rangle$ on the multiplicity $n$ of charged particles and on the kinematical variables of an associated hadron pair is studied. It is shown that $\langle E_{\mathrm{T}}^{\mathrm{ch}} \rangle$ at mid-rapidity increases almost linearly with increasing $n$: for $n > 6$, each additional produced hadron pair increases the maximum transverse energy density, $(\mathrm{d}E_{\mathrm{T}}^{\mathrm{ch}}/\mathrm{d}y)_{\max}$, on average by $0.27 \pm 0.01$ GeV. The mean transverse energy carried by charged hadrons accompanying a "trigger" dimeson with small transverse momentum (<0.5 GeV/$c$)

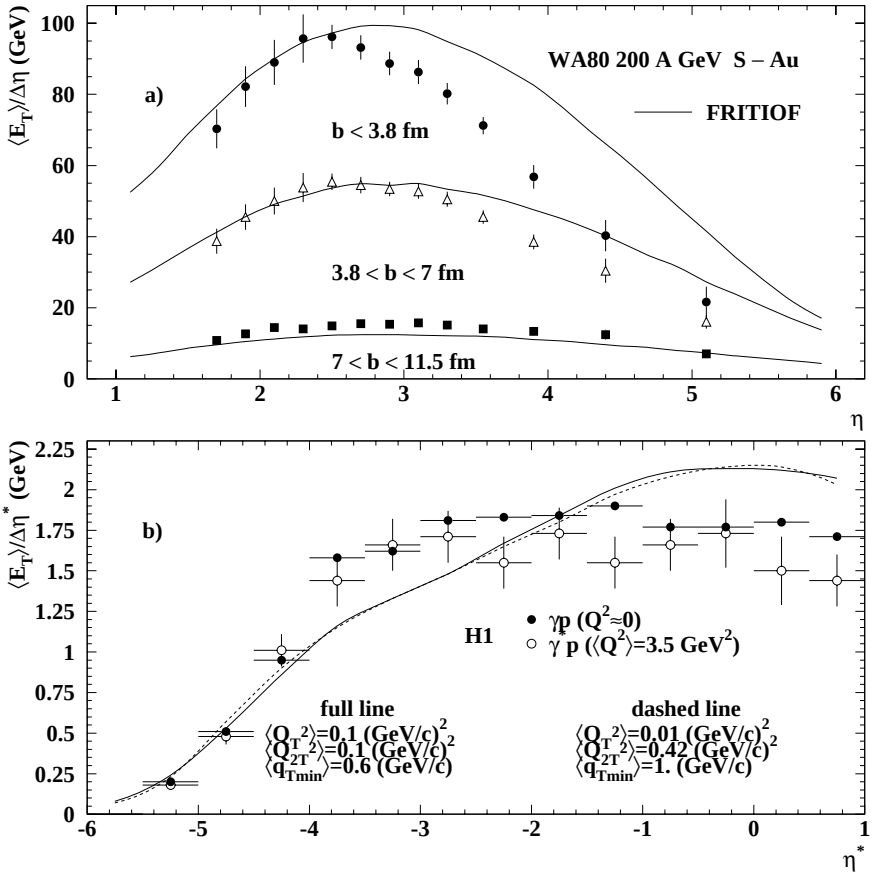


**Fig. 9. a** The pseudo-rapidity dependence of the transverse energy at different centralities of 200$A$ S+Au collisions as compared to FRITIOF7.0 predictions (the curves). **b** The pseudo-rapidity dependence of the transverse energy in the hadronic c.m.s. in $\gamma$p interactions at W$\approx$180 GeV and $\gamma^*$p at HERA, compared to FRITIOF7.0 predictions for $\pi$p interactions (the curves)

is smaller by about 30% than for the case of a high $p_{\rm T}$ (>2 GeV/$c$) "trigger" dimeson; this fact should be taken into account when extracting the mean impact parameter (corresponding the measured value of $E_{\rm T}$) in very peripheral nucleus-nucleus collisions.

The influence of nuclear effects on the $\langle E_{\rm T}^{\pi^-} \rangle$ production at mid-rapidity and in the target and beam fragmentation regions is investigated. This influence is maximal in the target fragmentation region, being reduced with increasing (pseudo)rapidity and being almost the same for the light (Al) and heavy (Au) nuclei at the largest (pseudo)rapidities. At mid-rapidity, the maximum value of $\langle E_{\rm T}^{\pi^-} \rangle$ per unit rapidity varies from $0.337 \pm 0.001$ GeV for meson-proton interactions to $0.49 \pm 0.01$ and $0.59 \pm 0.01$ GeV for meson-aluminium and meson-gold interactions, respectively.

The data are compared with predictions of the FRITIOF7.0 model with parameters tuned on inclusive spectra of positively and negatively charged particles produced in non-diffractive $\pi^+$p interactions at 250 GeV/$c$. The model describes well the data on $\langle E_{\rm T}^{\rm ch} \rangle$ and $\langle E_{\rm T}^{\pi^-} \rangle$ for meson-proton interactions, as well as on $\langle E_{\pi^-} \rangle$ at mid-rapidity in meson-nucleus interactions. The model qualitatively reproduces the data on $E_{\rm T}$ in peripheral proton-nucleus and heavy-ion collisions, but fails for more central ones. The comparison of the model predictions for higher energy $\pi$p interactions ($\sqrt{s}$=180 GeV) with the H1 photoproduction and deep-inelastic data reveals a similarity in the photon and pion fragmentation ($\eta^* < -4$), but the model fails at larger $\eta^*$ ($-4 < \eta^* < 1$).

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